Final Report

AOARD Number: 084038

Research Title:

"Growth and Characterization of low density InAs/GaAs quantum dots (QD) for quantum information processes"

Principal investigator:

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Period of Performance: 21 MAY 2008 – 20 MAY 2009

Final goal :

Growth and characterization of low density QD substrate for quantum information processes

Background

Semiconductor single quantum dot (QD) in a μ-cavity offers many potential applications in quantum information processes such as an all-optical quantum gate[1)], a single-photon source (SPS) for the quantum cryptography[2)] and entangled states[3)] for the quantum computation. For such applications, large QDs with a low density are desirable in practical senses, since a large single QD in a micro-cavity can provide better quantum functionalities with its large oscillator strength and strong coupling with the cavity mode. Furthermore, since large QDs have shown a temperature-insensitive exciton emission peaks up to 40 K, these can offer temperature-insensitive design and operation of SPS and all-optical quantum gates.

Photonic crystal (PC) has been widely studied since it provides not only high-Q wavelength-selective μ-cavity with a dimension comparable to wavelength of photons in it but also waveguide to couple out the photons in the μ-cavity. Therefore, PC-based μ-cavity with large QDs can be a important device for quantum cryptography and quantum computing.

Uniqueness of Approach and Method of Investigation

Since many QDs in a micron-sized (or wavelength-sized) μ-cavity can interfere each other to avoid single-QD based functionality, low-density QDs are desirable for an easy manipulation of them through standard semiconductor device fabrication processes and test processes. In our approach to grow low density In(Ga)As/GaAs QDs, we have introduced growth interruption between the deposition of In, (Ga), and As to control the formation of QDs [4)], which is different

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14. ABSTRACT
The aim of this project was to study the characteristics of the large QDs in a PC-based -cavity and finally develop the single photon source t. Better understanding of large QDs without -cavity would lead to better understanding of the large QDs with -cavity. So, the PI studied the large single QD and coupled QD further on their optical properties. Design of PC-based -cavity should be followed for the growth and fabrication of photonic-crystal based -cavity with low density In(Ga)As/GaAs QDs, which can act as a single photon source. The final goal of the 3-year project is to develop the PC-based single photon source with large In(Ga)As/GaAs QDs.

15. SUBJECT TERMS
Compound semiconductor, Epitaxial Crystal Growth, Optical Devices, Photonic Crystals

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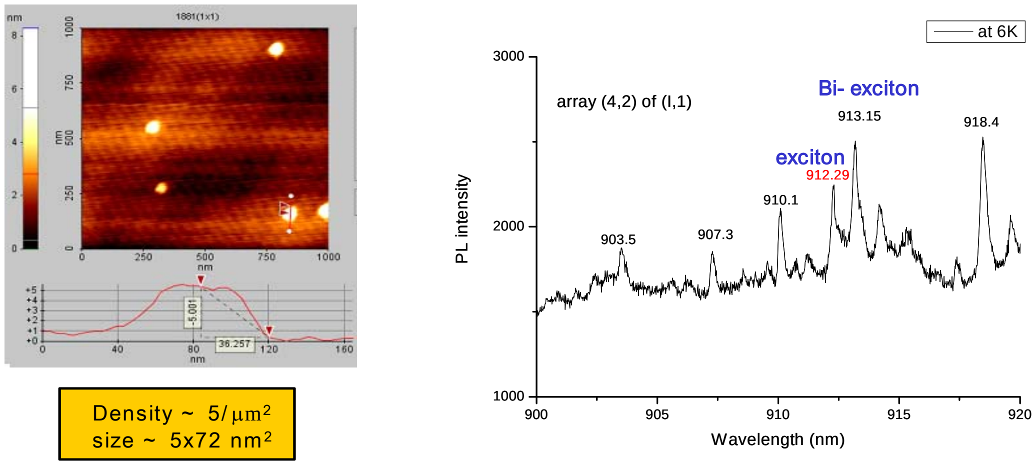
from the conventional method called Stranski-Krastanov (SK) method in which the deposition of In, (Ga), As is carried out simultaneously. In our approach to grow low density InAs/GaAs QDs, we could control the size and density of QDs by controlling the interruption time. By using our technique, we could grow low density In(Ga)As/GaAs QDs. The density of InAs/GaAs and InGaAs/GaAs were ~ 0.5 /μm^2 and 5/μm^2. Especially, InGaAs QDs showed large size ~5x72 nm^2 (Fig. 1). Since large QDs can provide large oscillator strength and strong coupling with the cavity mode of μ-cavity, the PC-based μ-cavity with a large QD in it can support better understanding of semiconductor-based quantum electrodynamics and provide the basic device for quantum cryptography and quantum computing.

In this project, we will study the characteristics of the large QDs in a PC-based μ-cavity and finally develop the single photon source with it. Better understanding of large QDs without μ-cavity would lead better understanding of the large QDs with μ-cavity. So, we will study the large single QD and coupled QD further on their optical properties. Design of PC-based μ-cavity should be followed for the growth and fabrication of photonic-crystal based μ-cavity with low density In(Ga)As/GaAs QDs in it, which can act as a single photon source. The final goal of the 3-year project is to develop the PC-based single photon source with large In(Ga)As/GaAs QDs.

Followings are topics to be studied in this 3-year project.

1. Characterization of exciton behaviors in a large single In(Ga)As/GaAs QD.
   - Measurement of carrier lifetime of exciton, biexciton in a single large In(Ga)As/GaAs QD
   - Bunching and anti-bunching experiments with a large single In(Ga)As/GaAs QD.
2. Optical characterization of low density coupled In(Ga)As/GaAs QDs.
3. Design of PC-based μ-cavity.
4. Growth and fabrication of photonic-crystal based μ-cavity with low density In(Ga)As/GaAs QDs in it.
5. Single photon generation with PC-based μ-cavity with large In(Ga)As/GaAs QDs

Preliminary Results (the result of the 1st year)



(a) (b)

Fig. 1 AFM image (a) and μ-PL spectrum of low density InGaAs/GaAs QDs

The above figure shows AFM (atomic force microscopy) image and m-PL spectrum of InGaAs/GaAs QDs grown with MEMBE (Migration Enhanced Molecular Beam Epitaxy). The size of InGaAs/GaAs QD is 5x72 nm^2. The exciton (912.27 nm) and bi-exciton (913.15 nm) peaks were identified with power dependent PL measurement. Our InGaAs/GaAs QDs shows emission wavelength near 910 nm with large size.

Figure 2 shows temperature dependent μ-PL spectra. One can see the exciton peak up to 40 K without any change in its emission wavelength. This is particularly interesting for the design of temperature-insensitive single photon source.

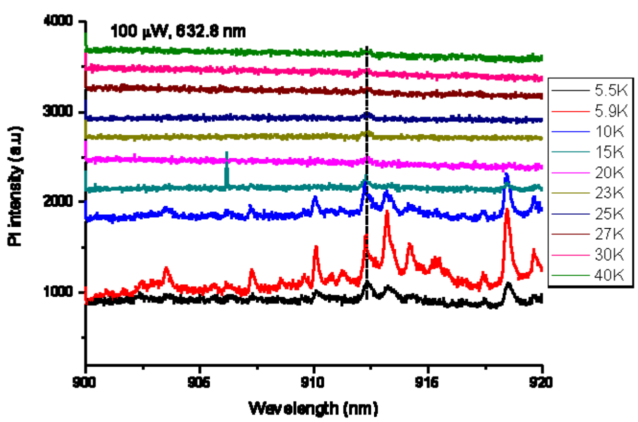


Fig. 2 Temperature dependent μ-PL spectra of low density InGaAs/GaAs QDs

Potential Applications

- Single photon source for quantum cryptography.
- Physical supports for all-optical quantum gate and the realization of Bell state for quantum information processing.
- All-optical logic gate for quantum computing.

References

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4. N. K. Cho, et al., Appl. Phys. Lett., 88, 133104 (2006)

Related (international) Project in Korea

The research topic is supported by GRL (Global Research Lab) program of MOST (Ministry of Science and technology, Korea) under the research MOU between KIST and CNRS, France. The French side is supported by LIA (Lab International Associated) program for an international collaboration. The domestic partner is KAIST (Prof. Yong-Hee Lee's lab). The French partners are Institute Neel (Prof. Le Si Dang's group) and Institute of Nanotechnology at Lyon (INL) (Dr. Christian Seassal's lab). The domestic partner and the French partner (INL) are doing their own PC-based micro-cavity design with our large QDs and the Le si Dang's group in French side supports the spectroscopic measurements of single QD and QDs in a micro-cavity. KIST focuses the research efforts to grow large QDs wafer for PC-based micro-cavity to support the design group. KIST also has spectroscopic measurement system at longer wavelength (> 1000 nm) to measure single QD emitting longer wavelength.

Accomplishments to Date:

During the course of this work, the following have been accomplished: 1) Development of droplet epitaxy techniques by MBE. 2) The growth of GaAs QDs and GaP anti-dots on GaAs substrates. 3) The growth of quantum molecules such as InAs QDs-GaP anti-dots, and GaAs coupled quantum dots. Results for experiments on hybridization of quantum states with the combination of quantum dots and anti-dots are still pending.